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AN ANNOTATED BIBLIOGRAPHY ON FREEZING AND THAWING OF SOILS

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AN ANNOTATED BIBLIOGRAPHY ON FREEZING AND THAWING OF SOILS

By Jesse Lunin[1]

Much of the past work on freezing and thawing of soils has been done by investigators interested primarily in the engineering aspects. However, the subject also is of great interest to soil scientists, because it is closely related to soil erosion, watershed hydrology, and drainage problems. Although some of the investigations to date are applicable to these problems, there is a great need for additional information. The following are some phases of the subject requiring further study:

- Factors affecting the temperature at which freezing takes place and depth of frost penetration in soils. This includes such items as mulches, snow, plant cover, soil moisture, salinity, soil color and texture, organic matter content.
- Water distribution and movement in frozen soils and during periods of thaw.
- Effect of freezing and thawing and of snowmelt on runoff and soil loss.
- Soil and crop management practices to minimize the adverse effects of freezing and thawing and of snowmelt.
- Effect of freezing and thawing on physical and chemical properties of soils.
- Improved instrumentation and laboratory techniques for studying the processes of freezing and thawing, and characterizing frozen soils.
- Thermodynamics of heat transfer and water movement in frozen soils.
- Factors affecting the formation of different types of ice and frost in soils and standardization of descriptive nomenclature.
- Heaving in soils and its effect on crop growth.
- Factors affecting water use by winter crops on frozen soils.
- Effect of fertilizer practices on plant resistance to frost.

The following references and abstracts[2] of the literature pertaining to freezing and thawing of soils are included because of their potential application to the solution of agronomic problems. The investigations reported include many phases of the subject, ranging from the theoretical aspects to the more practical applications.

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[1] Soil Scientist, Northeast Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture.

[2] An abstract enclosed in quotation marks is from the abstracting journal mentioned. The Highway Research Board Bibliography No. 3 ("Frost Action in Soils") provided some abstracts either quoted or revised.

Abbe, C. Ice columns in gravelly soil. U.S. Monthly Weather Rev. 33: 157-158. 1905.

Description and explanation of the phenomenon of slender columns of ice (needle ice, hoar frost) found at the surface of gravelly soil in moist places after a clear cool night.

Anderson, A. B. C., Fletcher, J. E., and Edlefsen, N. E. Soil-moisture conditions and phenomena in frozen soils. Amer. Geophys. Union Trans. 23: 356-364. 1942. (Contains Bibliography.)

A basic treatment of the thermodynamic theory involved in the interpretation of soil-moisture phenomena in frozen soils. A theoretical discussion of experimental methods of measuring the temperature at which soil moisture freezes; interrelations among the thermodynamic variables of state under different conditions of freezing soil moisture; generalized treatment of the effect of pressure on the freezing-point and its application to relatively moist soil (generalized Clausius-Clapeyron equation); and movement of soil moisture in relation to freezing phenomena in soils.

Anderson, H. W. Soil freezing and thawing as related to some vegetation, climatic and soil variables. Jour. Forestry 45: 94-101. 1947. (Abs. in Soils and Ferts. 10: 285. 1947.)

"Observations were made over 5 years in soil-temperature pits of the depth of freezing in (1) bare soil, (2) soil under a light grass cover of 15% density, and (3) under brush with 1/2 inch of litter and 30% canopy density during winter. No freezing occurred in (3), and on the average the first freezing of the year occurred 17 days earlier and the last freezing 45 days later in (2) than in (1). Lack of freezing in (3) was associated with higher minimum 1/2-inch soil temperatures which averaged 9.3° F. higher for November and 4.5° F. for February than in (1). Minimum air temperatures required to start soil freezing were 31° for (1), 29° for (2), and 14° for (3).

"Freezing the bare soil had an important effect on the content and distribution of moisture in the soil profile. Surface freezing drew water upwards from depths as great as 36 inches, causing the soil to become very damp and resulting in large evaporation losses compared with the combined transpiration-evaporation losses from [the] brush-covered soil. The high surface soil moisture caused by freezing was also associated with high run-off and erosion rates from bare soil."

Andrianov, P. I. Soil moisture. Inst. Merzlotovedeniya im. V. A. Obrucheva Trudy (Transactions of the V. A. Obruchev Institute for the Study of Permanently Frozen Soil, Moscow, Leningrad) 3: 5-138. 1946. [In Russian, with English summary.] (Contains Bibliography.)

A review of present (c. 1940) state of knowledge on behavior and characteristics of water content of soils, intended as bases for study of properties of permanently frozen soil.

Atkinson, H. B., and Bay, C. E. Some factors affecting frost penetration. Amer. Geophys. Union Trans. 21: 935-947. 1940.

Results of field experimental study to determine the effect of depth and density of snow cover and depth of straw cover on depth of frost penetration on plots of ground. Control plots were kept free of snow.

Barsukov, L. N., and Bakhareva, Z. I. The role of frost in the annual cycle of the structural condition of soil. Pochvovedenie 1950: 21-31. 1950. [In Russian.] (Abs. in Soils and Ferts. 13: 183. 1950.)

"Previous work had suggested that the variable effectiveness of spring cultivations might be due to the varying effects of different types of frost on the chemical properities of the soil. It had been shown in laboratory experiments that single freezing caused a reduction in acidity and solubility of sesquioxides and an increase in P solubility, but [that] repeated freezing increased acidity and sesquioxide solubility.

"The varying effect of single and repeated freezings was measured by the active surface and hygroscopicity of soils, determined according to formulae (not given) from the difference in moisture content when the soil was dried to constant weight at 40° and 60° C. A single freezing at -15° for 7 days caused a rise in both active surface and hygroscopicity, while two further freezings at 3-day intervals caused a progressive drop (below the control) in both properties, particularly in the hygroscopicity. When freezing was repeated immediately after thawing, the active surface decreased as in the first experiment but to a lesser extent, but the hygroscopicity increased progressively.

"Measurements of freezing-point depressions showed that one freezing lowered the freezing point, and repeated freezings lowered it further, but only if an interval of 1-3 days occurred between each thawing and freezing. When the soil was sterilized with toluene, no depression of freezing point occurred when freezing was done immediately after adding [the] toluene, but a large depression occurred when freezing was done a day later. This showed that the depression was caused by products of autolysis of bacterial bodies killed by the toluene. Further evidence was adduced purporting to show that the decrease in soluble Al following freezing of soil was due to the action of products of bacterial autolysis."

Bay, C. E., Wunnecke, G. W., and Hays, O. E. Frost penetration into soils as influenced by depth of snow, vegetative cover and air temperatures. Amer. Geophys. Union Trans. 33: 541-546. 1952. (Abs. in Soils and Ferts. 16: 30. 1953.)

"Plaster-of-Paris blocks were located at intervals in soil profiles to a 36-in. depth. As soil water freezes, unit resistance rises sharply. Dense vegetative and snow cover insulate soil and reduce rate of freezing and thawing. Winter wheat gave very little protection. 18 in. of snow did not prevent frost penetration to 12 in. when average minimum temperature was -21° F., but 24 in. of snow did. Graphs are given showing frost movement under varying depths of snow. Soil thaws from both surface and lower frost line."

Belotelkin, K. T. Soil freezing and forest cover. Amer. Geophys. Union Trans. 22: 173-175. 1941.

Concerns depth and time of soil freezing and rapidity of thawing as related to type of forest cover; also concerns effect of snow cover, forest litter, natural internal soil drainage, and soil texture on frost penetration.

Benkelman, A. C., and Olmstead, F. R. A new theory of frost heaving. Highw. Res. Bd. Proc. 11: 152-165. 1931.

Bennett, E. F. Frost action in soils. In Purdue University, Conference on Soil Mechanics and its Applications, Symposium on Frost Action, Sept. 2-6, 1940, Proceedings, pp. 471-473. 1940.

Benninghoff, W. S. Interaction of vegetation and soil frost phenomena. Arctic 5: 34-44. 1952. (Abs. in Soils and Ferts. 16: 30. 1953.)

"Permafrost in the north of Alaska is continuous with a frozen layer of 8-20 m. [;] farther south it is discontinuous. At shallow depths it creates a shallow soil with a hard impervious substratum. Vegetation, particularly mosses, shields the soil from maximum penetration of heat by shading, decreasing circulation, retaining soil moisture, and intercepting rain. During thaws more heat is transferred through water-saturated peat into the underlying soil than through dry peat. Clearing the land has a beneficial influence on the thermal regime of the upper soil layers during warm months of the year."

Berggren, W. P. Prediction of temperature distribution in frozen soils. Amer. Geophys. Union Trans. 24: 71-77. 1943.

Included are: Analysis of an idealized system, solution of examples, and special adaptations of the analysis.

Beskow, G. Soil freezing and frost heaving with special application to roads and railroads. Sweden Geol. Soc. 26th Yearbook, Ser. C, No. 3. 1935. [Published in Swedish in 1935; English translation by Northwestern Univ. Inst. Technol., 1947.] (Contains Bibliography.)

A treatise on frost action based on comprehensive studies in Sweden and on a critical review of previously published literature. Included are data and discussion on: History of frost studies; discontinuous frozen soil; the process of soil freezing; factors that determine the type of frozen soil; factors determining arrangement of ice layers; the process of frost heaving; freezing of nonsaturated soils; effect of pressure on heaving; water content increase; capillarity; hygroscopicity; permeability; suction; stratification (soil structure); ground water; and temperature of freezing soil.

__________ Scandinavian soil frost research of the past decade. Highw. Res. Bd. Proc. 27: 372-383. 1947.

Bethlahmy, N. Why do plants wilt in cold weather? Jour. Ecol. 33: 301-303. 1952. (Abs. in Soils and Ferts. 16: 387. 1953.)

"Results of studies with Colman Fibreglas soil-moisture units indicate that ground freezing is as important as protoplasm injury in causing death of plants. The Colman unit is described, and the resistance offered by the soil solution at varying concentrations and temperatures is illustrated diagrammatically. A dry soil and a frozen soil both offer very high resistances, and a hard frozen soil offers a resistance greater than that obtained at the wilting point of the soil. Data obtained indicate that a frozen soil is physiologically a dry soil and [that] a plant growing in frozen soil has no moisture available for growth and if it transpires it will wilt. A plant whose roots are below the frost line will not wilt, neither will a plant covered with snow."

Beylot, R. Potash and winter frosts in 1947. Potasse 22: 93-94. 1948. [In French.) (Abs. in Soils and Ferts. 11: 259. 1948.)

"From observations on three plots of wheat given different fertilizer treatments it is concluded that the resistance shown by the wheat of a 50-acre plot to the severe frosts of 1947 [was] due solely to the application of 250 kg. of K_2O as sylvinite."

Bodman, G. B., and Day. P. R. Thermoelectric method of determining the freezing points of soils. Soil Sci. Soc. Amer. Proc. (1937) 2: 65-71. [1938.]

The authors state objections to the commonly used method of determining freezing points of soils by means of the Beckman thermometer and describe equipment for thermoelectric measurement of freezing points. Experimental data are given concerning the effect of precooling temperatures on the freezing point as well as data on freezing point depression-moisture content relationships.

Bouyoucos, G. J. An investigation of soil temperatures and some of the factors influencing it. Mich. Agr. Expt. Sta. Tech. Bul. 17, 196 pp. 1913.

The results are given of heat conductivity experiments on natural soils (gravel, sand, loam, clay, and peat), and the effect of snow cover on soil temperatures. Also given are data on the freezing point of solutions in sand (NaCl, KCl, K_2CO_3, $CaCl_2$, and $(NH_4)_2CO_3$) and on the effect upon rate of rising and lowering of temperatures by the following admixtures: NH_4Cl, K_2HPO_4, K_2CO_3, K_2SO_4, $NaNO_3$, and $CaCl_2$.

__________ Effect of temperature on some of the most important physical processes in soils. Mich. Agr. Expt. Sta. Tech. Bul. 22, 63 pp. 1915.

__________ Effect of temperature on movement of water vapor and capillary moisture in soils. Jour. Agr. Res. 5: 141-172. 1915.

Covers test apparatus, test methods, experimental data, and theory of movement of moisture from warm soil to cold soil at various initial moisture contents. Includes data on both vapor movement and capillary movement of moisture and relation of temperature to surface tension and viscosity of water.

Bouyoucos, G. J. Soil temperature. Mich. Agr. Expt. Sta. Tech. Bul. 26, 133 pp. 1916.

The author reviews his previous work (Technical Bulletin 17, 1913) on specific heat and conductivity tests and presents voluminous soil temperature data taken during 1913, 1914, and 1915. He also discusses the effect of meteorological elements on the soil temperature; also daily and monthly maximum and minimum temperatures, monthly amplitude, and degree of amplitude for different depths and the law it follows.

__________ Degree of temperature to which soils can be cooled without freezing. Jour. Agr. Res. 20: 267-269. 1920.

Gives the results of experimental studies to determine the limit of supercooling which soils can resist without freezing.

__________ Movement of soil moisture from small capillaries to the large capillaries of the soil upon freezing. Jour. Agr. Res. 24: 427-431. 1923.

The author presents data showing the effect of alternate freezing, thawing, stirring, and standing on the freezing-point depression of soils. From the data he arrives at a hypothesis on the movement of moisture from small to large capillaries.

__________ A new electrical resistance thermometer for soils. Soil Sci. 63: 291-298. 1947.

Description of two new types of liquid electrical resistance thermometers for measuring soil temperature under field conditions.

__________ and McCool, M. M. The freezing point method as a new means of measuring the concentration of the soil solution directly in the soil. Mich. Agr. Expt. Sta. Tech. Bul. 24, 44 pp. 1916.

A correlation exists between the concentration of the soil solution and the freezing point of the soil. Further discussion is given in Technical Bulletin 31, 1916 by the same authors.

__________ and McCool, M. M. Further studies on the freezing point lowering of soils. Mich. Agr. Expt. Sta. Tech. Bul. 31, 51 pp. 1916.

A test method and procedure is discussed, and the principle of that method, for the determination of freezing-point lowering of soils; experimental data are presented. The authors discuss the relation between freezing point of soil and weight of solid matter and osmotic pressure; significance of unfree water on the determinations; and the effect of successive freezings on lowering of the freezing point.

Bouyoucos, G. J. and McCool, M. M. A study of the causes of frost occurrence in muck soils. Soil Sci. 14: 383-389. 1922.

The authors present air and soil temperature data and discuss the effect of soil color; differences in temperature of air at various elevations above ground; differences in specific heat according to volume of soil; and the effect of differences in heat conductivity on the occurrence of frost in muck soils.

__________ and McCool, M. M. The correct explanation for the heaving of soils, plants and pavements. Agron. Jour. 20: 480-491. 1928.

Three different types of heaving are described and explanation is given of the causes of frost heaving. Formation of ice crystals and movement of soil moisture associated with crystal formation are discussed.

Bridgeman, P. W. Effect of pressure on the freezing point of water. In Smithsonian Physical Tables, Smithsn. Misc. Collect. No. 71, 200 pp. 1921.

Table showing the "Effect of pressure on the freezing point of water."

Brooks, F. A., and Rhoades, D. G. Daytime partition of irradiation and the evaporation chilling of the ground. Amer. Geophys. Union Trans. 35: 145-152. 1954. (Abs. in Soils and Ferts. 17: 333-334. 1954.)

"The present study concerns daytime conduction and convection at the ground; how added soil moisture magnifies the heat-flow cycle; and how latent heat of vaporization offsets the diurnal temperature cycles. Measured diurnal cycles of net radiation, conduction, and convection for dry ground are described by formulae to show how the amplitudes and phase lag of half-cycle temperature and conduction waves indicate the partition of energy at the ground surface. A series of four test plots of 5 acres each was studied during spring frosts in a pear orchard. Two plots were disc-cultivated and one of these was immediately flood-irrigated lightly. The observed diurnal magnitudes of heat flow were more than twice as great in the watered plot as in the unirrigated. The striking results are not the effect of disc cultivation, but rather of the chilling caused by application of water. The watered plot took more than ten days (in April) to recover from the evaporation chill, but then warmed up more than the other three plots and two weeks after flooding was definitely less liable to frost than the unwatered plots. The use in the formulae of total daily water loss from the soil provides a fair understanding of the diurnal thermal system.--From authors' summary."

Brown, R. T., and Potter, G. F. Relations of fertilizers to cold injury to tung trees occurring at Lucedale, Mississippi, in March, 1948. Amer. Soc. Hort. Sci. Proc. 53: 109-113. 1949. (Abs. in Soils and Ferts. 13: 135. (1950.)

"Trees that had received liberal applications of N and K over a period of 7 years suffered practically no loss of bearing surface and set a full crop. The average loss of bearing surface on unfertilized trees, many of which were killed, was severe, and the crop was reduced by 75 to 80%. The factors involved in cold resistance are discussed."

Bryan, K. Cryopedology--the study of frozen ground and intensive frost action with suggestions on nomenclature. Amer. Jour. Sci. 244: 622-642. 1946.

Buettner, K. A small portable meter for soil heat conductivity and its use in the O'Neill tests. Amer. Geophys. Union Trans. 36: 827-830. 1955.

Bunt, J. S. The effect of freezing and thawing on the surface structure of certain soils at Macquarie Island. Austral. Jour. Sci. 17: 36. 1954. (Abs. in Soils and Ferts. 18: 33. 1955.)

"A corrugated structure of sloping ground, filled with angular rock fragments in the hollows and composed of silt and clay on the crests is believed to be caused by thawing of the mostly frozen soil. Drainage would be restricted to the path of ice formation, which is oriented in parallel rows, causing gradual removal of finer fractions and formation of slight hollows."

Burton, V. R., and Benkelman, A. C. The relation of certain frost phenomena to the subgrade. Highw. Res. Bd. Proc. 10: 259-275. 1930.

Results of field pavement-condition surveys and laboratory studies of frost action. Included are data on frost action as related to soil type and soil profile in cut and fill section, and data taken in the freezing of cylinders of soil in the laboratory.

___________ and Benkelman, A. C. Frost action in silt soils defined by field and cold room studies. Engin. News-Record 106: 266-270. 1931.

Byrnes, W. R. Effect of soil texture on occurrence and type of ground freezing. Jour. Forestry 49: 786. 1951. (Abs. in Soils and Ferts. 15: 252. 1952.)

"Comparison was made of a loamy sand, a silt loam, and a clay loam. At 0° and 15° F. the concrete type of frost structure occurred in the mineral soil of all three textures, regardless of whether they were at field capacity or saturation. Litter and humus layers prevented the occurrence of concrete frost. Even when frozen the litter and humus layer can absorb water whereas concrete frost in the mineral soil is quite impermeable."

Cailleux, A. Études de cryopédologie. Paris, Centre de Documentation Universitaire, 68 pp. 1948. (Publications des Expéditions Polaires Françaises, No. 3).

Comprehensive account based mainly on western European and American studies.

Campbell, R. B. Freezing point of water in puddled and unpuddled soils at different soil moisture tension values. Soil Sci. 73: 221-229. 1952.

Samples of soil of different texture were brought to equilibrium on porous membranes at soil-moisture tensions ranging from 1/3 to 15 atm., and were subsequently subjected to several successive freezings by the normal procedure or by adiabatic freezing. Curves are presented showing relationships of soil-moisture tension or freezing-point depression to moisture percentage, also showing the influence of alternate freezing and thawing on the freezing-point depression. Moisture content at the same moisture-tension level was higher, and freezing-point depression at the same moisture content was larger, in puddled than in unpuddled soils. At the same moisture tension, clay loam gave smaller freezing-point-depression values than did loam or fine sandy loam; and larger decreases in freezing-point depression were observed between the first two freezings than between later freezings. Larger decreases in the freezing-point depression were observed between the first and second freezing than between any two later freezings. Average observed freezing-point-depression values obtained from soils frozen adiabatically were not significantly different from values obtained from cores frozen by the normal method. The reasons for differences between soil-moisture-tension data calculated from freezing-point depression and obtained on pressure membranes are briefly discussed.

Cannel, G. H., and Gardner, W. H. Freezing-point depressions in stabilized soil aggregates, synthetic soil, and quartz sand. Soil Sci. Soc. Amer. Proc. 23: 418-422. 1959. (Abs. in Soils and Ferts. 23: 105. 1960.)

"The freezing-point depression of soil moisture, determined by using a small probe-type thermistor as the sensing element, increased with decreasing size of aggregates separated from conditioner-treated silt loam. The same trend occurred in different sized sand separates. Successive freezing and thawing decreased the freezing-point depression for soil aggregates much more than it did for sand separates. In a synthetic soil prepared from ground quartz and illitic clay, freezing-point depression for aggregates of 1-2 mm. diameter increased with increasing rates of IBMA (copolymer of isobutylene and the half NH_4 salt-half NH_2 of maleic acid) applied as a conditioner. Increasing undercooling temperatures increased freezing-point depression in non-aggregated synthetic soil, but had little effect in the silt-loam soil or sands."

Carlson, H. Calculation of depth of thaw in frozen ground. Highw. Res. Bd. Spec. Rpt. 2, pp. 192-223. 1952. (Abs. in Soils and Ferts. 16: 109. 1953.)

"Work in Russian, Scandinavian, and American literature is reviewed and conditions necessary for the existence of perma-frost, depth of thaw, and depth of frost penetration are discussed, computed, and illustrated with graphs."

Carson, J. E. Soil temperature and weather conditions. Argonne Natl. Lab. ANL-6470. 1961.

Carter, C. L. Soil temperature, moisture content, and thermal properties. Univ. Tenn. Engin. Expt. Sta. Bul. 15, 85 pp. 1958.

Casagrande, A. Discussion on frost heaving. Highw. Res. Bd. Proc. 11: 168-172. 1931.

Commonwealth Bureau of Soil Science. Bibliography on relationships between soil freezing, temperature and moisture (1941-1960). Commonwealth Bur. Soil Sci. [Bibliog.] 370, 8 pp. 1960. (Annotated.)

Crabb, G. A., Jr., and Smith, J. L. Soil-temperature comparisons under varying covers. Highw. Res. Bd. Bul. 71, pp. 32-47. 1953.

Crawford, C. B. Soil temperature--a review of the literature. Highw. Res. Bd. Spec. Rpt. 2, pp. 17-40. 1952.

Czeratzki, W. Clod structure of soil from autumn to spring. Landbauforsch. 5: 8. 1955. [In German.] (Abs. in Soils and Ferts. 19: 158. 1956.)

"Photographs show the destruction of clod structure in loess and clay soil under the effect of early winter rains and its partial reconstruction, especially in clay soil, under the influence of alternate freezing and thawing."

__________ The process of soil freezing. Landbauforsch. 6: 86-87. 1956. (Abs. in Soils and Ferts. 20: 89. 1957.)

"Twelve photographs of the various phases of soil freezing are interpreted."

__________ The effect of frost on soil structure. Ztschr. f. Pflanzenernähr., Düngung u. Bodenk. 72: 15-32. 1956. [In German.] (Abs. in Soils and Ferts. 19: 253. 1956.)

'Determinations on frozen and unfrozen soils in the field and laboratory showed a considerable increase of moisture in the frozen layers that was gained from moisture in the immediately underlying layers and by capillary rise from the groundwater. The increase of moisture due to freezing was greater in fine sands and loamy soils (e.g., loess) or at high compaction than in coarse sands and clayey soils or at slight compaction. Excessive increase in moisture by freezing, which may be twofold in loess, results, at thawing, in a destruction of aggregates formed during the winter and even of the crumb structure of the preceding autumn. The beneficial effects of frost are most marked in plowed clay soils. Soil heaving by frost ranged from 3.4 cm. in sandy clay loam to 8.9 cm. in sand. Photographs show homogeneous and heterogeneous frost structures in different soils, and the relationship of frost structures to structural grades by the 'spade diagnosis' is discussed. 30 references to the effects of frost on soil structure are briefly reviewed."

Danilin, A. I. The use of gamma-radiation in investigations of the water regime of soils and of the snow cover. Akad. Nauk SSSR, Izv., Ser. Geog., 3: 103-109. 1959. [In Russian; German Abs. in Ref. Zhur. (Biol.), No. 85357, 1960.] (Abs. in Soils and Ferts. 24: 344. 1961.)

"The scheme presented is for vertical and horizontal radioscopy of soil and for measurement of the evaporation from surface soil. The method was used for determining the moisture reserve of the snow cover and the regime of thawing."

Decker, A. M., Jr., and Ronningen, T. S. Heaving in forage stands and in bare ground. Agron. Jour. 49: 412-415. 1957. (Abs. in Soils and Ferts. 20: 330. 1957).

"Heaving during the winter and early spring, as determined by weekly measurements of the upward movement of wooden dowels driven to 4-16 inches depth in the soil, was related to changes in soil temperature and to the uniformity and density of the plant cover. Alternate freezing and thawing caused considerable heaving [of] bare soil and [the soil] under shallow-rooting ladino clover which provided a sparse cover and was damaged by heaving. The degree of heaving decreased with [the] improving soil cover provided by orchard grass > brome grass > lucerne > Kentucky bluegrass. Dowels driven deep into the soil heaved less than those placed to shallow depth."

Diebold, C. M. Effect of vegetation upon snow cover and frost penetration during the March 1936 floods. Jour. Forestry 36: 1131-1137. 1938.

Domby, C. W., and Kohnke, H. The effect of freezing and thawing on structure of the soil surface. Agron. Jour. 47: 175-177. 1955. (Abs. in Soils and Ferts. 18: 316. 1955.)

"Periodic determinations were made over a period of two years of the bulk density and water stability in the surface inch of a silt loam kept bare or under 2 tons/acre straw as surface mulch or suspended 3 inches above the soil. In the mornings, frozen blocks of soil were measured and their volumes calculated and moisture contents determined gravimetrically; in the afternoons, the bulk densities and moisture of thawed soil were determined with 13.6-ml. sampling cans about 1/2 inch deep. There was a rapid structural breakdown during the winter in bare soil, but compaction occurred in winter even under mulch. Accumulation of ice in the frozen surface layer caused soil heaving, and thawing during the day was accompanied by slumping down of the soil surface. Decreases of up to 30% occurred in the bulk density of soil during freezing, but the ultimate result of alternate freezing and thawing during the winter was an increase of bulk densities from 1.15 g/cc to 1.35 g/cc with a loss of about half the volume of large pores, both in bare and mulched soil. Diurnal variations of structure were less in mulched than in bare soil, probably due to a less frequent and not so uniform accumulation of ice. Soil below the zone of alternate freezing and thawing was driest when the surface was frozen and wettest when the surface had thawed; this variation in moisture content affected bulk density more than did the expansion of freezing water."

Dreibelbis, F. R. Some influences of frost penetration on the hydrology of small watersheds. Amer. Geophys. Union Trans. 30: 279-282. 1949. (Abs. in Soils and Ferts. 12: 255. 1949.)

"Frost penetration retards percolation, retains water in the profile which normally would drain, and through its influence on percolation and resultant available storage may affect infiltration for a considerable time after the frost period. Records are discussed of frost penetration and hydrological data for the Muskingum-silt-loam catchment 109 at Coshocton. In spite of low precipitation in February and March when deep frost prevailed, the profile was almost saturated. In April, May, and June, with precipitation above normal, the soil-moisture content remained so high that oats and maize sowings were much delayed. In grassland and woodland the more porous frost structure (honeycomb and stalactite) is common, while cultivated land favours the production of the deep and more impermeable concrete type."

Ducker, A. Soil colloids and their behavior when subjected to frost action. Bauingenieur 23: 235-237. 1944. [In German; English translation, Dec. 1944, by H. B. Edwards, Engin. Dept. Res. Centers, U.S. Waterways Expt. Sta., Vicksburg, Miss.] (Contains Bibliography.)

Review and discussion of the Schmid and the Casagrande criteria for appraising the effect of frost on a soil; discussion of data determined in freezing tests on soil colloids.

Eimern, J. van. Observations of and remarks on the movement of moisture and frost-heaving in soil. Ztschr. f. Acker- u. Pflanzenbau 108: 375-383. 1959. [In German] (Abs. in Soils and Ferts. 22: 360-361. 1959.)

"In a heavy soil with a low water table, the magnitude of soil-heaving was recorded during the winter season in relation to soil temperature and moisture and snow cover. Soil-heaving occurred immediately after the start of frost and reached a maximum of 23 mm. at a time when the soil contained 20% moisture to a depth of 50-60 cm. Soil-heaving was only 16 mm. at [the] lower soil-moisture levels (20% moisture to 30 cm. depth) despite the greater depth of frost penetration to 37 cm. as compared with 23 cm. at the time of greater heaving."

Ekblaw, W. E. The importance of nivation as an erosive factor and of soil flow as a transporting agency in northern Greenland. Natl. Acad. Sci. Proc. 4: 288-293. 1918.

A description of the process of nivation (the formation and melting of snow-ice) and its effect on the disintegration of rocks; destruction of some land forms and the formation of others. A description is also given of solifluction (soil flow) and its connection with nivation.

Endell, K., Loos, W., and Breth, H. Zusammenhand zwischen Kolloid-chemischen sowie bodenphysikalischen Kenziffern bindiger Boden und Frostwirking. Forschungsarbeiten aus dem Strassenwesen, Band 16, 55 pp. 1939.

Relationship between colloid chemicals as well as soil-physico-chemical indices of cohesive soils and frost action.

Evans, D. D., Horrigan, J. A., and Chinn, C. E. Temperature-time curves as soil freezes related to moisture stress curves. Soil Sci. Soc. Amer. Proc. 22: 375-378. 1958.

The rate of cooling of a moist soil sample during freezing is determined by the rate of heat dissipation to the surroundings and the rate of ice formation within the sample. Assuming equilibrium conditions at an instantaneous temperature, the amount of ice formed between two temperatures depends upon the amount of water held in the sample between the soil moisture stresses associated with the two temperatures. Temperature-time curves (freezing curves) during freezing have been obtained for soils using a thermistor and recording potentiometer. The curves have been related to moisture-stress curves derived through the use of standard pressure apparatus. A method is presented which may allow the construction of a moisture-stress curve from one freezing of a single sample of soil.

Fuller, H. U. Frost penetration as affected by weather and snow conditions. New England Water Works Assoc. Jour. 50: 299-301. 1936.

A discussion of frost penetration, depth of snow blanket, depth of frost penetration, and temperature deficiency (freezing index) at Portland, Maine.

__________ Studies of frost penetration. New England Water Works Assoc. Jour. 54: 275-281. 1940.

Gandahl, R. Determination of frost depth with a simple type of measurer. Grundförbättring 10: 7-19. 1957. [In Swedish.] (Abs. in Soils and Ferts. 20: 204. 1957.)

"The instrument [to determine frost depth] consists essentially of a plastic-glass tube 1-1/2 m. long and graduated in 5-cm. divisions, and filled with distilled water coloured with methylene blue. Ice crystals which form when the water freezes are not coloured by the methylene blue. The tube is inserted in the ground and withdrawn for observation. The depth to which freezing has occurred is measured by the depth to which the contents of the tube are colourless. The construction of the apparatus is described in detail and full instructions for its use are given."

__________ and Burgau, W. Two methods for measuring the frozen zone in soil. Proc. 4th Interntl. Conf. Soil Mech. and Found. Engin., London, 1: 32-34. 1957.

Gardner, R. Some effects of freezing and thawing on the aggregation and permeability of dispersed soils. Soil Sci. 60: 437-444. 1945.

A discussion of the effect of freezing on soil aggregation and permeability, with experimental data on restoration of structure to puddled saline (sodium) soils; and the effect of freezing on the permeability of dispersed soils.

Garstka, W. V. Hydrology of small watersheds under winter conditions of snow cover and frozen soil. Amer. Geophys. Union Trans. 25: 838-1060. 1944.

Gilboy, G. Soil mechanics research. Amer. Soc. Civ. Engin. Proc. 57: 1185-1186. 1931.

An explanation of the mechanics of frost action based on results of field laboratory studies cooperative between U.S. Bureau of Public Roads, the State of New Hampshire, and M.I.T.

Gold, L. W. Influence of snow cover on heat flow from the ground. Assoc. Internationale d'Hydrologie Scientifique, Union Geodesique at Geophysique Internationale, Assembles Generale do Toronto 1957, Tome 4: 13-21. 1958.

Goodell, B. C. Soil boring tool for frost depth determination. Jour. Forestry 37: 457-459. 1939.

Goodell, B. C. Soil freezing as affected by vegetation and slope aspect. Jour. Forestry 37: 626-629. 1939.

Gradwell, M. W. Soil frost studies at a high country station. I. New Zeal. Jour. Sci. and Technol. 36B: 240-257. 1954. (Abs. in Soils and Ferts. 18: 132. 1955.)

"In depleted high-country tussock grassland at Molesworth, ground freezing often penetrates to depths of 2-3 inches during winter. In shady places the frozen condition may persist to the surface for several days at a time; elsewhere partial or complete thawing occurs on sunny days and is followed by re-freezing at night. Four distinct ice forms were observed. Only small scattered ice crystals occur under plant cover. Since heavy ice-needle formation is confined to patches of bare ground, these needles can only damage plants by exerting an overturning effect on them from the side. Maximum growth of needle ice occurs only in certain places and appears to be favoured by exposure to sunlight sufficient to promote a partial thaw during the day. It also requires a loamy soil of good water-holding capacity and a site not too well drained. Where most fully developed, ice needles can exert a very powerful effect in preventing the establishment of young plants on bare ground. This effect seems to be most pronounced in places otherwise providing good prospects for regeneration, i.e., moist loamy soils on level or moderately sloping sunny sites. Regions already heavily depleted, stony, and supporting little vegetation except scabweed show considerably less ice formation owing to better soil drainage.--From author's summary."

Grim, R. E. The clay minerals in soils and their significance. Ill. Geol. Survey Cir. 65: 11-12. 1941.

Relation of frost heaving to clay-mineral composition; the clay minerals discussed include montmorillonite, kaolinite, and certain illite soils.

__________ Relation of frost action to the clay-mineral composition of soil materials. Highw. Res. Bd. Spec. Rpt. 2, pp. 167-172. 1952. (Abs. in Soils and Ferts. 16: 110. 1953.)

"The relationship of frost action and frost heaving in montmorillonite, kaolinite, illite, halloysite, vermiculite, and attapulgite-palygorskite soils, and the influence of salts added to soils are discussed."

Hale, C. E. Some observations on soil freezing in forest and range lands of the Pacific Northwest. U.S. For. Serv., Pacific Northw. Forest Expt. Sta. Forest Res. Notes No. 66, p. 17. 1950. (Abs. in Soils and Ferts. 14: 457. 1951.)

"There are indications that frost has a decided effect on the entry of spring snowmelt water to subsoil under Ponderosa pine and grass and under grass and sagebrush in eastern Oregon and [eastern] Washington. In the Ponderosa pine/grass type, surface runoff from melting snow occurred over 1 in. of soil freezing."

Haley, J. F. Cold-room studies of frost action in soils. A progress report. Soil temperature and ground freezing. Highw. Res. Bd. Bul. 71, pp. 1-7. 1953.

Cold-room tests are being performed to determine the effects of individual factors considered to influence ice segregation in soils. (1) The intensity of ice segregation in soils is dependent not only on the percentage of grains finer than 0.02 mm. but also on grain size distribution or the physical-chemical properties of these fines. (2) Fine soil fractions with high percentage of fine clay sizes appear to be more effective than silt sizes in producing ice segregation in soils. (3) The intensity of ice segregation in a frost-susceptible soil varies directly with the initial degree of saturation. (4) The rate of heave of the surface is generally independent of rate of freezing within the range of 1/4-1-3/4 in. per day, but the heave per unit depth of frozen material is inversely proportional to the rate of penetration of the freezing temperature. (5) The percentage of heaves of samples with fine soil fraction (less than 200 mesh) is in the order of kaolinite, illite, and montmorillonite.

__________ and Kapler, C. W. Coldroom studies of frost actions in soils. Highw. Res. Bd. Spec. Rpt. 2, pp. 246-267. 1952. (Abs. in Soils and Ferts. 16: 110. 1953.)

"Tests were made to determine the effects of individual factors which influence ice segregation in soils, such as percentage of fine particles, percentage of stone, permeability, capillarity, proximity of water supply, compaction, and initial degree of saturation. Equipment and methods used are described."

Harrold, L. L., and Roberts, R. L., Jr. Winter runoff from snow and frozen ground. Mich. Quart. Bul. 43:154-169. 1960. (Abs. in Agr. Res. Serv. (U.S. Dept. Agr.), ARS 41-50, No. 21, p. 44. 1961.)

"In 1940 a research project, designed to study and evaluate the important factors in snow and frozen ground hydrology, was established at Michigan State University, East Lansing, Michigan. Two cultivated watersheds were extensively instrumented on University land, and one wooded watershed at the nearby Rose Lake Wildlife Experiment Station.

"The area of each of the three watersheds is about two acres. The aspect of the two cultivated watersheds is N-NW. The average slope of watershed A is 6%, and that of watershed B is 6.5%. The soils of the watersheds are well-drained fine sandy loams and loamy fine sands and of glacial origin. Both watersheds were basically in a rotation of corn with cover crop, oats, and two years of hay.

"The data and discussion in this report constitute only a simple graphical presentation of basic summaries of some measured factors which are believed to influence precipitation-runoff relations during periods of freezing and thawing of the soil mantle and accumulation and melting of snow. It is clearly apparent, however, that the relationships among the factors shown on the graphs are not simple."

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Henin, S., Locussol, L., and Robichet, O. Relationships between some aspects of frozen soil and structure. [Paris] Acad. des Sci. Compt. Rend. 241: 80-82. 1955. [In French.] (Abs. in Soils and Ferts. 18: 496. 1955.)

"Porous bricks and tiles were sunk level with the surface of wet soil. When completely saturated, they were sprinkled with soil particles. After a night of slight frost each particle was raised on a "stalk" of ice 1-2 cm. high. There was no raising when frost was severe. To study the development of the "stalks" a porous cylinder was filled with water and pushed into wet soil, open end downwards. The porous surface had previously been rubbed with oily paper in one area, which remained free from ice while the rest was coated with a layer 0.5 cm. thick. After remaining in place for several days of freezing and thawing, the oiled part was coated with hair-like crystals, evidently growing from their bases where the oil film was perforated. [In another experiment] kneaded rods of damp soil were left to freeze, some on bare soil, some on paper resting on soil, and others were kept in a refrigerator at 2° C. Frozen and unfrozen rods were placed in flasks of water or alcohol and gently shaken for 4 hr., then passed through sieves of 2 and 0.2 mm. mesh. Results show that the rods were split up by ice crystals, the wetter the soil the more marked the effect. Particles $>$ 2 mm. formed 66.5% of the rods in contact with soil, 82% of those on paper, and 100% of those kept at 2° C. The same order held for particles $>$ 0.2 mm., but differences were smaller. Ice lamellae formed at about 30° to the axes of the rods."

__________ and Robichet, O. Observations on the freezing of soil and its agronomic consequences. [France] Min. de l'Agr., Inst. Natl. de la Rech. Agron., Ann., Ser. A, Ann. Agron. 1: 732-747. 1950. [In French.] (Abs. in Soils and Ferts. 14: 221. 1951.)

"With sudden intense frost a layer of vertically orientated ice crystals of 1-2 cm. length was observed at the limit of the depth of freezing in a moist, humus-rich soil, the region above this containing much smaller crystals intimately mixed with soil particles. In a sandy soil, identical climatic conditions produced very similar results but the ice layer here was only about 1 mm. thick. With gradual establishment of cold conditions, freezing begins in crevices between [the] surface lumps and the general soil mass and extends upwards, forcing up clods of soil which tend to make a cylindrical shape. Freezing of the internal moisture of these leads to their swelling and finally to disintegration of their outer surface. On very moist soils a smooth compacted surface induces the formation of superficial lamellar ice crystals, while a crumb structure leads to development of acicular crystals tending to extend perpendicularly to that portion of the crumb surface on which they originate.

"The impermeability of frozen soil may lead to erosion by run-off. A wet thaw [tends to] degrade soil structure, but stability may increase if thawing occurs during a dry spell. Alternate swelling and sinking of the top soil in a series of frosts were investigated by driving in wooden and iron stakes, which were progressively forced out, more rapidly in loose than in firm soil. Factors increasing the uprooting of cereal seedlings by frost were shallow sowing, coarse tilth, and high soil humidity."

__________ and Robichet, O. The mechanism of soil lifting due to frost. [Paris] Acad. des Sci. Compt. Rend. 232: 2358-2360. 1951. [In French.] (Abs. in Soils and Ferts. 14: 374. 1951.)

"Observations on frozen soils, ranging from sands to medium clays, showed that the constitution of the ice crystals was influenced by the duration of the frost and by the crumb structure of the soil. The soil surface was lifted by up to 2 cm. in soils frozen 22 cm. deep, the magnitude of the raising not being proportional to the depth of the frozen layer, [being] greater with loose than with packed soils. The theory is put forward that the lifting of the soil is due to the upward rise and displacement of water occurring during freezing rather than to its expansion."

Higashi, A. On the thermal conductivity of soil, with special reference to that of frozen soil. Amer. Geophys. Union Trans. 34: 737-748. 1953.

Based upon the Angstrom principle, a new apparatus for measuring the thermal diffusivity of soil was designed, and the thermal diffusivity of frozen and of wet soil was measured. Thermal conductivity was computed from the diffusivity and the volume specific heat of the soil. Moisture relationships of the thermal diffusivity and the conductivity of frozen soils are represented by an empirical formula of exponential form. Samples of various modes of segregation of ice were artificially prepared and their thermal diffusuvity measured.

Highway Research Board (National Research Council). Frost action in soils. Highw. Res. Bd. Bibliog. 3, 57 pp. 1948. (Annotated.)

__________ Frost action in soils, a symposium. Highw. Res. Bd. Spec. Rpt. 2, 385 pp. 1952.

__________ Soil temperature and ground freezing. Highw. Res. Bd. Bul. 71, 124 pp. 1953.

__________ Soil freezing. Highw. Res. Bd. Bul. 100, 35 pp. 1955.

Holmes, R. M., and Robertson, G. W. Soil heaving in alfalfa plots in relation to soil and air temperature. Canad. Jour. Soil Sci. 40: 212-218. 1960. (Abs. in Soils and Ferts. 23: 401. 1960.)

"Measurements made by the use of a simple instrument (which is described) showed the protective effect of snow cover on frost heaving which apparently proceeds under conditions of fluctuating soil and air temperatures near the freezing point. Alternate freezing and thawing seems to promote heaving by favouring the accumulation of water near the soil surface. Only slight heaving occurs in soils of low moisture content during periods of steady cold." (See Penner, 1961, p. 23)

Jackson, K. A., and Chalmers, B. Study of ice formation in soils. U.S. Army Corps of Engineers Tech. Rpt. 65, rev. 1957. (Arctic Construction and Frost Effects Laboratory, Boston, Mass.)

A theory of nucleation of ice in water during freezing is outlined. Nucleation temperatures in water are discussed in terms of surface energy of water molecules, contact angles, and cluster size. Major factors involved during freezing of soil moisture are outlined. The application of the nucleation theory to the freezing of soils is discussed. It is indicated that the force of heaving is dependent upon the amount of supercooling present in the soil moisture. An attempt is made to develop a qualitative theory of soil freezing and heaving.

Johnson, W. C. Frost heaving, soil type, and soil water tension. Iowa State Col. Jour. Sci. 31: 452-453. 1957. (Abs. in Soils and Ferts. 20: 266-267. 1957.)

"The rate of soil expansion expressed in [millimeters per hour] (Q) was determined in undisturbed samples from the upper 2 ft. over a range of water tensions (p) in different soil types ($Q = \frac{b^2}{(p + cb)^2}$, where the constant b is inversely proportional to the cube of particle diameter and c varies from 1 in silts to zero in clays). The rate of heave of the soils was not closely related to their particle-size or pore-size distributions. The regression of the rate of expansion (Q) on rate of water absorption (W), converted to inches of ice/hr. was for one soil: $Q = .0219 + 1.024 (W - .0247)$. The rate of heaving was independent of the geometry of the freezing soil system and was unaffected by the barrier zone below the frost line restricting waterflow. Alternate freezing and thawing, and wetting and drying, were first reflected on a structureless soil in an increased rate of heave at tensions $>$ 100 cm. The treatment of soil with a detergent or silicone decreased the rate of heaving."

Jumikis, A. R. The soil freezing experiment. Highw. Res. Bd. Bul. 135, pp. 152-163. 1956.

__________ Soil moisture transfer in the vapor phase upon freezing. Highw. Res. Bd. Bul. 168, pp. 96-115. 1957.

__________ Some concepts pertaining to the freezing soil systems. Highw. Res. Bd. Spec. Rpt. 40, pp. 178-190. 1958.

__________ Concerning a mechanism for soil moisture translocation in the film phase upon freezing. Highw. Res. Bd. Proc. 39: 619-639. 1960.

The discussion in this article centers on the theory of a possible mechanism for the soil moisture translocation upon freezing. A review is given of the electric double-layer theory. Both the discussion and the review show that the property of a colloidal soil particle of carrying on its surfaces an electrical charge and the capability of soil moisture films surrounding the particles to act as electrolytes are of basic significance in the process of the translocation of soil moisture in the film phase. This phase is set in motion by an external primary thermal potential, i.e. by freezing.

Jurgenson, L. Field test for identification of soil capable of frost heaving (English summary). Proc. 1st Internatl. Conf. Soil Mech. and Found. Engin., Harvard Univ., 2: 171-173. 1936.

A rapid field test to identify susceptibility of soils to frost. The test is based on rate of settlement when soil is suspended in water, the quantity of fines being related to the depth of sediment.

Juusela, T. K. On the freezing of cultivated soils and the effect of draining on freezing and thawing. Suomen Maataloustiet. Seura, Maataloustiet. Aikakausk. 13: 82-95. 1941. [In Finnish, with German Summary.] (Abs. in Soils and Ferts. 10: 414. 1947.)

"The influence on soil freezing of air temperature, the intensity and thickness of the snow cover, the type of soil and its particle size, the structure and treatment of the tilled layer, the nature of the plant cover, the groundwater level, and the moisture and heat content of the soil are discussed. Soils provided with open ditches appear to freeze to a depth 10-15% greater than those with drains, but it cannot be concluded definitely that this is caused by differences in ground-water level, as freezing of soils with open ditches can be affected by arching the strip between the ditches and improving heat conduction. Investigations have shown that the higher the groundwater level at the time of freezing the greater the frozen-soil water content. In drained areas, frozen soil is also of coarser structure so that a considerable part of the melted snow can penetrate the frozen soil and accelerate thawing."

Kerstan, M.S. Thermal properties of soils. Univ. Minn. Inst. Technol. Bul. 28, 221 pp. 1949. (Cited in Highw. Res. Bd. Spec. Rpt. 1. 1952.)

Our knowledge of thermal properties has increased considerably during the past few years. Numerical values of the various constants permit mathematical checks of various heat-transfer problems in connection with frost action in soils. Numerical values of specific heat and thermal conductivity are given in this paper, for use in calculation of diffusivities. Use of these values and additional research may lead, it is hoped, to corrections and improvements in the stated values. It should be noted that most of the thermal-property information available is from laboratory tests. The need for field checks is apparent.

Kirpaneva, L. I. The effect of frost on soil structure. Akad. Selak. Khoz. Nauk Dokl. 11: 37-41. 1959. [In Russian.] (Abs. in Soils and Ferts. 23: 104. 1960.)

"Laboratory experiments showed that after freezing and thawing the soil aggregates are relatively unstable, but recover their stability when left undisturbed in the absence of excess water. The aggregates remain unstable in the presence of excess water."

Koepf, H. Investigations on crumbs formed under frost. Landw. Forsch. Sonderh. 7: 69-73. 1956. [In German.] (Abs. in Soils and Ferts. 19: 335. 1956.)

"The aggregate stability of crumbs in various frosty soils was determined mainly by McCalla's water-drop method. The stability showed a positive correlation with the clay content of the soil and was particularly affected by the geological origin of the parent material; it was unrelated to pH and $CaCo_3$ or humus contents of the soil. The stability of air-dry crumbs was lower than that of moist crumbs and increased to an optimum with moisture content increasing to 20-30%."

Kolesnikov, A. G. A modification of the mathematical formulation of the problem of soil freezing. Akad. Nauk Dokl. 82: 889-891. 1952. [In Russian.] (Abs. in Soils and Ferts. 16: 361-362. 1953.)

"Only water in the free state is transformed into ice during soil freezing. Combined water freezes later with significant decrease of soil temperature below freezing point. The increase of ice in the soil causes a decrease of specific heat and an increase of thermal conductivity of the soil. Equations taking into consideration these peculiarities are presented."

Komarov, V. D. Investigations on the water permeability of frozen soil. Met. Gidrol. 2: 10-18. 1957. [In Russian.] (Abs. in Soils and Ferts. 22: 356. 1959.)

"Absorption of water by frozen soil is accompanied by its partial freezing since the lower soil layers experience a rise in temperature as the result of the latent heat liberated in the freezing of water. Whether frozen soil remains permeable when melt water trickles through it or whether it rapidly becomes impermeable depends on the cold reserve of the soil, the amount of frozen water which melts at negative temperatures, and the cross section areas of the free pores before melting begins."

Kretschmer, G. Frost-induced water movement in soil and its effect on plants. Deut. Landw. 7: 199-200. 1956. [In German.] (Abs. in Soils and Ferts. 20: 89. 1957.)

"Since the freezing of percolating water of weak surface tension and of hygroscopic water of high surface tension occurs at different temperatures, the freezing of pore water proceeds gradually, continually removing water from the still moist layers and resulting first in the formation of ice crystals and subsequently in that of ice layers. This and a similar process in the roots may lead to the withering of plants, and soil heaving may result in the rupture of roots."

Lane, K. S. Treatment of frost sloughing slopes. Proc. 2d Internatl. Conf. Soil Mech. and Found. Engin., Rotterdam, 3: 281-283. 1948.

Larin, P. A. Water permeability of frozen soils tilled in various ways. Pochvovedenie No. 11, pp. 89-93. 1961. [In Russian, with English summary.] (Abs. in Soils and Ferts. 25: 107. 1962.)

"The infiltration rate of water into frozen chestnut soil before the snow had melted decreased as the soil-moisture content in autumn increased and practically ceased when the autumn moisture content was high. Infiltration into frozen soil after moldboard plowing to 25 or 40 cm. was twice as rapid as infiltration into stubble [soil] or after moldboardless plowing to 30 cm. and was twice as great after moldboard plowing + mole drainage as after moldboard plowing alone. The permeability of frozen soil to air also decreased with increasing moisture content in autumn."

Larson, W. E., Burrows, W. C., and Hazen, T. E. Equipment and methods for measurements of soil temperature. Agr. Res. Serv. (U.S. Dept. Agr.), ARS 41-27, 10 pp. 1959.

Logsdail, D. E., and Webber, L. R. Effect of frost action on structure of Haldimand clay. Canad. Jour. Soil Sci. 39: 103-106. 1959. (Abs. in Soils and Ferts. 23: 30. 1960.)

"Moisture-saturated surface samples of soil equilibrated at pressures of 1-0.003 atm. (32.5-85.9% moisture) were subjected to three cycles of alternate freezing and thawing. Treatments caused a significant breakdown of aggregates in well-aggregated soil (from bluegrass-sod plots), the destructive effects increasing with increasing moisture; no significant breakdown occurred in poorly-aggregated soil (from continuous-maize plots) at any moisture level."

Mackintosh, A. Progress report on an investigation of frost action in soils. Proc. 1st Internatl. Conf. Soil Mech. and Found. Engin., Harvard Univ., 2: 260-262. 1936.

A description of the cold room and equipment for temperature measurement at Harvard University and a report of progress in a determination of the magnitude of force associated with the growth of ice in soil.

Martin, R. T. Rhythmic ice banding in soil. Frost effects in soils and on pavement surfaces. Highw. Res. Bd. Bul. 218, pp. 11-23. 1959.

A comprehensive theory is presented to explain rhythmic ice banding, which produces a type of frost heave in soil. Theory is divided into four phases: (a) Nucleation of ice at some distance from an existing ice frost, (b) rapid growth of this nucleus into an ice lens, (c) termination of crystal growth, (d) heat and water flow.

Miller, R. D., Baker, J. H., and Kolaian, J. H. Particle size, overburden pressure, pore water pressure and freezing temperature of ice lenses in soil. Trans. 7th Internatl. Cong. Soil Sci. 1: 122-129. 1960. [In English, with French and German Summaries.] (Abs. in Soils and Ferts. 25: 204. 1962.)

"The effects of overburden pressure and pore-water pressure are additive. Precedence of ice entry over air entry into soil pores (due to the greater interfacial tension of an air-water interface than ice-water interface) means that heaving should occur only when the soil just beneath the ice lens is fully wetted. A continuous air phase should not exist in unfrozen soil next to a growing ice lens. Results provide a basis for the use of 'capillarity' (air-entry value) for judging the susceptibility of soils to heaving. Hydraulic flow in unsaturated unstratified soil cannot sustain lens growth, except in aggregated soil where intro-aggregate pores are empty."

Molchanov, A. A. Freezing and thawing of soil. Lesn. Khoz. 1: 27-31. 1950. [In Russian.] (Abs. in Soils and Ferts. 14: 130. 1951.)

"There exists a connexion between the character of snow cover and the depth of freezing of soil. Determination of depth of freezing by thermometers is not precise, because freezing point varies with physical and chemical composition of soil. Heavy lime soils do not freeze even at temperatures much below the usual [winter temperature of] -0.1 to -0.5° C. The speed of thawing varies, the daily mean ranging from 8 to 0.1 cm., and is highest in pine forests and lowest in bare fields."

Moore, C.B. Air temperature and frost penetration. Maine Water Util. Assoc. Jour. 12: 46-48. 1936.

Mosienko, N. A. The water permeability of frozen soil in the Kulundin steppe. Pochvovedenie No. 9, pp. 122-127. 1958. [In Russian, with English summary.] (Abs. in Soils and Ferts. 22: 31. 1959.)

"A formula is given for calculating the amount of thaw water absorbed by permeable frozen loamy soil (southern leached chernozem). Frozen soils whose pores contain ice, i.e., those which were excessively moist before freezing began, are impermeable until this ice melts. Permeability is restored when their moisture content [becomes] $<$ 60-65% of field capacity. Soils in which $>$ 50% of the total porosity is free are permeable to water irrespective of their temperature. The coefficients of run-off in spring were 0.21 after autumn plowing across the contour, [and] 0.68 from hay meadow and 0.38 from maize stubble [land]."

Motuzov, Ya. Ya. The effect of frost on the structure and resistance of soil to erosion in relation to soil moisture. Pochvovedenie No. 3, pp. 53-58. 1960. [In Russian, with English summary.] (Abs. in Soils and Ferts. 23: 261. 1960.)

"A preliminary freezing and thawing of soil monoliths taken at a depth of 15-25 cm. from peat-gley soil decreased infiltration into the soil columns when the soil was at its maximum moisture capacity. At 60% of the total moisture capacity, freezing and thawing increased infiltration. The optical density of the filtrates from unfrozen soil was six times greater than that of filtrates from soil previously frozen and thawed. At 60% of the total moisture capacity, freezing and thawing decreased the porosity of the 5-7 mm. aggregates by 13%, but field experiments showed that the total porosity of sod-meadow soil was higher immediately after the thawing of frozen soil than it was subsequently. Soils which are excessively wet in late autumn and soils in which the capillary fringe is not very deep so that moisture can move freely towards the freezing layer are more susceptible to erosion [at snowmelt] in spring than are soils with an optimal moisture content at the time of freezing."

Murai, N. A study of snow cover and frozen soil in relation to slope erosion. Hokkaido Univ. [Sapporo, Japan]. Expt. Forests, Res. Bul. 17: 769-792. 1955.

Tables and graphs show air and soil temperatures, precipitation, snow cover, and depth of freezing of three different sites. Snow cover and depth of soil freezing influence winter erosion, and even more so that of the summer.

Nikki, I. Studies on root injury to some crops caused by the formation of the ice layer, and on protection measures. 1. Formation of the ice layer. 2. Injuries to various crops. Crop Sci. Soc., Japan, Proc. 22: 9-12. 1953. [In Japanese, with English summary.] (Abs. in Soils and Ferts. 17: 334. 1954.)

"Damage to crops through frost-heaving of soil was very severe in legumes. Drought injury and soil erosion followed the thaw. A frozen profile is illustrated and described. The principles underlying soil freezing and thawing are discussed. Root damage to red clover, lucerne, vetch, Poa, rye, and rape is described."

__________ Studies on root breaking in some crops due to formation of an icicle-layer in the soil, and methods of protection. 3. Formation of ground-cavity and its relation to plant roots. Crop Sci. Soc., Japan, Proc. 23: 283-284. 1955. [In Japanese, with English summary.] (Abs. in Soils and Ferts. 18: 498. 1955.)

"The ice layer in frozen soil develops horizontally in regions where the root system is not too dense. The thickening of the ice layer causes soil heaving, leaving cavities in which the roots are stretched and ultimately broken. The more vigorous the root system, the deeper are the cavities formed; poorly developed roots may be cut directly under the plant, without formation of cavities. Cultivation promoting a vigorous root growth is apt to reduce this type of frost damage."

Orvedal, A. D., Kubota, J., and Smith, H. M. Major soil profiles and their relationship with climate. Highw. Res. Bd. Spec. Rpt. 2, pp. 1-9. 1952.

Penner, E. Soil moisture flow during ice segregation. Highw. Res. Bd. Bul. 135, pp. 109-118. 1956.

__________ Soil moisture tension and ice segregation. Fundamental and practical concepts of soil freezing. Highw. Res. Bd. Bul. 168, pp. 50-64. 1957.

The moisture tension developed in a closed system appears to be largely dependent on soil texture: The greater the proportion of fines, the higher the moisture tension, with more moisture thus made available for freezing. It is suggested that the freezing-point depression at the ice-water interface determines the soil-moisture tension which acts as the driving force during frost heaving.

__________ The importance of freezing rate in frost action in soils. Natl. Res. Council Canada, Div. Bldg. Res. April 1960.

__________ Alternate freezing and thawing not a requirement for frost heaving in soils. Canad. Jour. Soil Sci. 41: 160-163. 1961. (Abs. in Soils and Ferts. 25: 33. 1962.)

"Soil-freezing experiments in the laboratory and measurements on the floor of a cold-storage plant indicate that a cycle of alternate freezing and thawing is not needed for frost-heaving as suggested by Holmes and Robertson. [See p. 17.]--From author's summary."

Post, F. A., and Dreibelbis, F. R. Some influences of frost penetration and microclimate on the water relationships of woodland, pasture, and cultivated soils. Soil Sci. Soc. Amer. Proc. (1942) 7: 95-104. 1943.

Shallow frost depths generally provided stalactite and honeycomb types of frost structure; concrete structure was usually associated with deep freezing. Frost depth was inversely related to the amount of plant residues and to percolation. Depth of freezing was related to temperature only in a general way, being influenced also by soil moisture and porosity. The concentration of immobilized water at or near the soil surface was one of the most important characteristics of frozen soils.

Richards, L. A., and Campbell, R. B. The freezing point of moisture in soil cores. Soil Sci. Soc. Amer. Proc. 13: 70-74. 1949. (Abs. in Soils and Ferts. 13: 178. 1950)

"Mainly a progress report on the improvement of experimental procedure to resolve discrepancies among vapour-pressure, pressure-membrane, and freezing-point data. The freezing-point measurement is made with a metal-jacketed Type 14B Thermistor, the time required for successive determinations being 1-8 minutes, or only slightly greater than that required for the sample to reach a temperature maximum after freezing is initiated. Measurements on cores obtained with a sampling tube facilitate the preparation of samples and minimize disturbances that affect the freezing point of field samples."

Rosenfeld, L. M. The effect of processes of the crystallization of water in soil on the overwintering of plants. Agrobiologiya No. 5, pp. 70-79. 1949. [In Russian.] (Abs. in Soils and Ferts. 13: 28. 1950.)

"T. D. Lysenko (Agrobiologia No. 3, 1948, p. 341) attributes the overwintering of winter-sown cereals when sown in Siberia in the stubble of a preceding crop to the fact that in the uncultivated soil the ice crystals are so small (and so relatively few) that they do not damage the seeds or seedlings. It is the damage caused by large ice crystals present in loose, cultivated soils rather than low temperatures that prevents ordinarily cultivated crops from surviving a Siberian winter.

"The structure and quantity of ice crystals formed when soil freezes depend mainly on the temperature, moisture content, and compaction of the soil.

"Microphotographs taken in the laboratory of soils of different moisture content and compaction showed that the less the moisture and the greater the compaction the smaller were the ice crystals, and the lower was the temperature at which ice formation occurred."

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__________ and Gudkova, N. K. A field apparatus for determining the thermal characteristics of frozen soils and of the snow cover. Sborn. Trudov Agron. Fiz. 5: 126-133. 1952. [In Russian.]

Rowland, E. F., Stolzy, L. H., and Crabb, G. A. Frost determination by electrical resistance. Highw. Res. Bd. Bul. 100, pp. 17-21. 1955. (Abs. in Soils and Ferts. 19: 148. 1956.)

"A simple method is given for determining the start of freezing of soil moisture in situ. A characteristic 200-ohm increase in resistance indicated the commencement of freezing, and was always preceded by a period of stable temperature and resistance. Increases in resistance at temperatures below 32° F. [resulted from] dehydration due to freezing and indicated the degree of completion of crystallization. Freezing of mineral soils within the available moisture range began at temperatures of 31.00-31.75° F."

Shaw, B. T. Soil physical conditions and plant growth. Academic Press, New York, 492 pp. 1952.

Sigafoos, R. S., and Hopkins, D. M. Soil instability on slopes in regions of perennially-frozen ground. Highw. Res. Bd. Spec. Rpt. 2, pp. 176-192. 1952. (Abs. in Soils and Ferts. 16: 109. 1953.)

"Hill slopes are subject to less heaving and less severe subsidence than are marshy lowlands or hill summits. Soil terraces are formed on gentle slopes by heaving and subsidence. Lobate terraces occur on steeper slopes and result from heaving, subsidence, and viscous flow and a perennially frozen substratum is not necessary for their formation. Mudflows result from the sudden flow of semi-fluid soil and rock downslope when the turf has been broken by frost heaving or by the weight of the saturated soil."

Sillanpää, M. The dynamic nature of soil aggregation as affected by cycles of freezing and thawing. Acta Agr. Scand. 11: 87-94. 1961. [In Swedish.]

__________ and Webber, L. R. The effect of freezing-thawing and wetting-drying cycles on soil aggregation. Canad. Jour Soil Sci. 41: 182-187. 1961. (Abs. in Soils and Ferts. 25: 32. 1962.)

"Five cycles of wetting and drying increased the mean weight-diameter (M.W.D.) of large aggregates, but did not cause significant changes in the fractions $<$0.25 mm. Cycles of freezing and thawing at moisture contents near saturation significantly decreased the M.W.D. of large aggregates. A significant decrease occurred in the M.W.D. of the original aggregates $<$0.25 mm. at the slower rate of freezing.--From authors' summary."

Siple, P. A. Climatic aspects of frost heave and related ground frost phenomena. Highw. Res. Bd. Spec. Rpt. 2, pp. 10-16. 1952. (Abs. in Soils and Ferts. 16: 110. 1953.)

"Radiation, conduction and convection, and moisture problems are discussed."

__________ Ice-blocked drainage as a principal factor in frost heave, slump, and solifluction. Highw. Res. Bd. Spec. Rpt. 2, pp. 172-175. 1952. (Abs. in Soils and Ferts. 16: 110. 1953.)

"The theory is put forward that frost heave, slumping, and solifluction are caused by ice-blocked drainage in the soil."

Slater, C. S., and Hopp, H. The action of frost on the water-stability of soils. Jour. Agr. Sci. [England] 39: 341-346. 1949. (Abs. in Soils and Ferts. 12: 412. 1949.)

"Freezing and thawing decreased the water stability of moist soils, but the rate of freezing and thawing had no effect on the loss of water stability. Methods designed to overcome the harmful effects of frost action should be based on reducing the depth and frequency of freezing and on maintaining drainage channels in the soil layer where freezing occurs, so as to keep the moisture content as low as possible."

Soulides, D. A., and Allison, F. E. Effect of drying and freezing soils on carbon dioxide production, available mineral nutrients aggregation and bacterial population. Soil Sci. 91: 291-298. 1961.

Stepanov, L. N. Water permeability of frozen soils. Vopr. Agron. Fiz., pp. 185-199. 1957. [In Russian.] (Abs. in Soils and Ferts. 24: 111. 1961.)

"Frozen drained soils in which the volume of pores free from ice is more than 50% of the porosity are permeable. In monoliths frozen in the laboratory the permeability of frozen sandy soil was determined mainly by the moisture content of the soil before freezing. Water could infiltrate into loamy soils provided ice-free cracks were present. In frozen loamy soils, disturbed soil near drains was more permeable than [undisturbed] soil between the drains. Monoliths containing much ice were impermeable."

Stoeckeler, J. H., and Dartignoi, E. J. Snowdrifts as a factor in growth and longevity of shelterbelts in the Great Plains. Ecology 22: 117-124. 1941.

__________ and Thames, J. L. The Lake States penetrometer for measuring depth of soil freezing. Soil Sci. 85: 47-49. 1958. (Abs. in Soils and Ferts. 21: 236. 1958.)

"The penetrometer described consists of a 38-inch-long graduated steel probe of 1/2 inch or 5/16 inch diameter, sliding in a weighted driving hammer. The maximum depth of frozen soil that can be tested is 23 inches. The probe penetrates about 1/4 - 1/2 inch per stroke in hard-frozen ground and 4-8 times more when it breaks through the frozen zone. The penetrometer is useful in the rapid measurement of frost thickness in mineral and peat soils, where depth of freezing is generally < 12-16 inches, the operation taking 1-2 min. as compared with 5-10 times [this long] when excavating with pick and spade."

__________ and Weitzman, S. Infiltration rates in frozen soils of northern Minnesota. Soil Sci. Soc. Amer. Proc. 24: 137-139. 1960. (Abs. in Soils and Ferts. 23: 259. 1960.)

"[In] tests using single-ring steel cylinders on grassland and forest soils, infiltration in concretely frozen soil (dense freezing, preventing air passage) was 0.09 inch/hr. in silt loams and 0.47 inch/hr. in loamy sands. Infiltration in the loamy sands increased to 2.19 inches under conditions of porous-concrete frost (hard-frozen soil porous enough to permit blown air to pass through), and to 3.97 and 13.22 inches in partly frozen and unfrozen soil, respectively. While the impermeable type of concrete frost prevailed in grassland, the more permeable types tended to be present in forest."

Taber, S. Frost Heaving. Jour. Geol. 37: 428-461. 1929.

The experimental procedures are described; an explanation is given of ice segregation; and the following factors which influence frost heaving are discussed: Size and percentage of voids in soil, size of particle, water content of soil, rate of cooling. Included are discussions of depth of freezing, direction of cooling, external pressure, crushing strength of ice, differential heaving, effects of thawing and refreezing, shrinkage of clays caused by ice segregation.

__________ Discussion on frost heaving. Highw. Res. Bd. Proc. 11: 173-177. 1931.

A summarization of Taber's hypothesis on the mechanics of frost heaving, and discussion of the Benkelman and Olmstead theory.

Tigerman, M. H., and Rosa, J. M. Erosion from melting snow on frozen ground. Jour. Forestry 47: 807-809. 1949.

Turner, K. A., Jr., and Jimikis, A. R. Subsurface temperatures and moisture contents in six New Jersey soils 1954-1955. Factors influencing ground freezing. Highw. Res. Bd. Bul. 135, pp. 77-108. 1956.

(1) The greatest depth and rate of frost penetration occur in granular soils as a result of their high thermal conductivity, relatively speaking, as compared with the thermal conductivity of fine-grained soils. (2) The greatest depth of frost penetration does not necessarily occur at the same time as the minimum air temperature. (3) Maximum frost heaving does not necessarily occur simultaneously with maximum depth of frost penetration. (4) Soil freezes at temperatures slightly lower than 32° F.

Umetani, H. On the freezing phenomena of soil. Jour. Agr. Met. [Tokyo] 6: 173-175. 1951. [In Japanese, with English summary.] (Abs. in Soils and Ferts. 16: 281. 1953.)

"Various forms of frozen soil [result from] varying [amounts of] soil moisture, provided soil density and cooling rate (soil air) are constant. Classes of frozen soil were as follows: frost columns (> 50% water), concrete-like ([> 40]% water), stratified ice crystals and soil grains (33-40% water), no ice crystals (< 33% water). Isopleth charts show changes with depth in soil moisture on several days."

United States Corps of Engineers. Frost investigation, 1944-1945. Report on laboratory tests on frost penetration and thermal conductivity of cohesive soils. Appendix 13 to Comprehensive Report. 1945. (U.S. Engin. Off., Corps of Engineers, Boston, Mass.)

__________ Report of frost investigation 1944-1945. 66 pp. and 15 Appendixes. 1947. (U.S. Corps of Engineers, New England Division, Boston, Mass.)

United States Corps of Engineers. Review of the properties of snow and ice. SIPRE Report 4. 156 pp. 1951. (U.S. Corps of Engineers, Snow, Ice and Permafrost Research Establishment, Wilmette, Ill.; prepared by Univ. of Minn. Inst. of Technol.)

__________ Annotated Bibliography on Snow, Ice and Permafrost. SIPRE Report 12. [Vol. 1], 226 pp., 1951; Vol. 2, 356 pp., 1952. 1951-52. (U.S. Corps of Engineers, Snow, Ice and Permafrost Research Establishment, Wilmette, Ill.; prepared by the Library of Congress.)

__________ Frost investigations (Fiscal year 1951). Vol. 1, Cold room studies. 58 pp. and supp. tables and plates. 1951. (U.S. Office of the Chief of Engineers, New England Division, Frost Effects Laboratory, Boston, Mass.)

Vries, D. A. de, and Wit, C. T. de. The thermal properties of moor soils and the effect of a sand cover on the danger of night frost to these soils. Met. Rundschau 7: 41-45. 1954. [In German.] (Abs. in Soils and Ferts. 18: 131. 1955.)

"The heat conductivity of four Dutch humus soils with admixtures of sand and mud was measured and was also calculated theoretically at different moisture contents. The specific heat of two of the soils was measured. Covering soil with not more than 10-15 cm. of sand can be expected to reduce frost risk. Mixing the upper soil layers with sand has a similar, but smaller, effect[,] especially in dry periods."

Weger, N. Water movement and water content determination in frozen ground. Met. Rundschau 7: 45-47. 1954. [In German.] (Cited in Soils and Ferts. 18: 132. 1955.)

Willis, W. O. Freezing and thawing, and wetting and drying in soils treated with organic chemicals. Soil Sci. Soc. Amer. Proc. 19: 263-267. 1955. (Abs. in Soils and Ferts. 18: 496. 1955.)

"The effects of 1-20 cycles of freezing and thawing or of 1-10 cycles of wetting and drying on aggregate stability were studied in the laboratory on seven soils treated with 0.1% HPAN (a hydrolysed polyacrylonitrile), 0.2% SC-50 (a water-soluble sodium methyl siliconate), or 0.0013% PR-51 (a water-soluble alkylated aromatic sulphonate). In general repeated freezing and thawing and, to a lesser extent, wetting and drying decreased the percentage of aggregates > 0.25 mm. in untreated soils and in soils treated with SC-50 or HPAN. With freezing and thawing, untreated soils and soils treated with HPAN showed the greatest breakdown of aggregates during the first cycle, but with SC-50 [treatment] aggregate stability increased in the first cycle and decreased thereafter. Although wetting and drying caused a general decrease in aggregate stability with repeated cycles, an increase in aggregate stability may occur during some cycles. Lagonda soil treated with SC-50 was exceptional in having a greater aggregate stability after 10 cycles of wetting and drying than it had initially. PR-51 did not affect the response of soil to freezing and thawing or to wetting and drying."

__________ Carlson, C. W., Alessi, J., and Haas, H. J. Depth of freezing and spring run-off as related to fall soil-moisture level. Canad. Jour. Soil Sci. 41: 115-123. 1961.

Studies conducted at Mandan, N. Dak., evaluated the effects of fall soil-moisture level and snow depth on the depth of freezing and spring run-off. Results showed that soil which was dry in the fall froze faster and deeper than a wet soil. Insulative effects of snow increased with snow depth. In the spring, a dry profile thawed upward to the surface while a wet soil thawed both upward to and downward from the soil surface. Run-off in the spring was less from dry soil. Completion of run-off coincided with frost removal from the dry plots, but thawing was not complete in the wet soil until about 10 days after run-off had ceased. Time of run-off completion was the same for wet and dry soils.

Wilner, J. The effect of low temperatures on available soil moisture during winters of the Canadian prairies. Agron. Jour. 47: 411-413. 1955. (Abs. in Soils and Ferts. 19: 38. 1956.)

"Moisture determined by Bouyoucos's method in two winter seasons showed decreasing availability to depths of 12-18 inches with decreasing air temperatures. Moisture was unavailable to most of the feeding roots of box-elder trees during periods with temperatures of 2° -33° F. Occasional increase of air temperatures above freezing during these periods may stimulate metabolic activities and contribute to winter desiccation and permanent injury of woody plants."

Winterkorn, H. F., and Fehrman, R. G. The effect of freezing-thawing and wetting-drying cycles on the density and bearing power of five soils. Soil Sci. Soc. Amer. Proc. (1944) 9: 248-252. 1945. (Abs. in Soils and Ferts. 10: 36. 1947.)

"In compaction tests, the densities and bearing values were found to depend upon the texture, structure, and moisture content of the soils. Water exposure and cycle tests showed that after 4 days' immersion in water the bearing values of the soils were 3-11% lower than those found [for soils] at maximum density and optimum moisture content . . . which had not been immersed. Twelve freezing-thawing cycles lowered the bearing values of clay soils (but not of a fine sand) 1-5%. Freezing-thawing, followed by 12 days' water immersion had a greater effect upon bearing values than was expected from their final moisture contents. Twelve cycles of wetting and drying, and twelve of freezing and [wetting] reduced the bearing value of all soils practically to zero."

Yakuwa, R. The melting of frozen soil in Tokachi district, Hokkaido. Hokkaido Univ. [Sapporo, Japan], Faculty Agr.; Mem. 2: 1-6. 1955. [In Japanese, with English summary.] (Abs. in Soils and Ferts. 20: 25. 1957.)

"A mathematical treatment of melting by solar radiation."

Yamada, S. Effect of the freezing-thawing action of volcanogenous soils upon crops and remedial measures. I. Jour. Sci. Soil and Manure [Tokyo] 21: 268-274. 1951. [In Japanese, with English summary.] (Abs. In Soils and Ferts. 15: 187. 1952.)

"Volcanic-ash soils when frozen to 30-100 m. depth show alternative layers of frozen soil and ice pillars in the profile; on thawing, stagnant water covers the surface. Frozen volcanic pumice soils are filled with ice particles between the frozen[-in] pumices whose interior is dry; on thawing, there is little stagnant water, the melted ice being readily absorbed by the pumices. Volcanic sandy soils show characteristics of both types."

Yamada, S. Investigations on freezing and thawing actions of volcanogenous soils and their influences upon soils and crops. Part I. Soil and Plant Food [Tokyo] 1: 84-87. 1955. (Abs. in Soils and Ferts. 19: 256-257. 1956.)

"At the surface of ash soils, water columns freeze to form ice pillars up to 10 cm. long. Cracks appearing below the surface become packed with ice pillars as capillary water freezes. The pillars grow and the surface soil rises as water is supplied from below. With further decreases in temperature, lower layers are affected, forming alternating ice-pillar and frozen-soil horizons. In soft pumice soils, pumice grains in the upper horizons are dry except for a thin layer of surface moisture. This layer freezes and numerous small granular ice particles form between the pumice grains. In lower horizons the pumice grains contain more moisture which is frozen only on their surface and ice particles between the pumice are less numerous. In deeper unfrozen horizons, water is uniformly distributed in the pumice grains. In hard pumice soils the pumice grains have moist interors and freezing disintegrates them. Layers of ice pillars are not formed in pumice soils but minute ice needles form on the surface of the grains, and are longer in the surface soil than at greater depths. Volcanic sandy soils are intermediate between ash and pumice soils in their freezing effects. During thawing, the water in ash soils passes downward through cracks, and melts the upper ice horizon. Further melting of ice horizons is slow because of the frozen soil layer, and water flows along tunnels left by the melted ice horizon. In pumice soils during thawing, surface ice on the pumice grains melts rapidly, the grains absorb water, and drying of the soil is more rapid than in ash soils. Thawing and drying are also more rapid in volcanic sandy soils than in ash soils because the ice-pillar layers are thinner. Freezing and thawing is thus most injurious to plants on ash soils and least injurious on pumice soils. Volcanic soils dry more slowly than mineral soils do."

__________ and Tamura, S. Investigation on the freezing and thawing action of volcanic soil and remedial measures for soil and crops. 2. Jour. Sci. Soil and Manure [Tokyo] 23: 101-114. 1953. [In Japanese, with English summary.] (Abs. in Soils and Ferts. 18: 10. 1955.)

"In frozen volcanic soil, ice formation near the surface kills the roots of crops and grasses and nursery trees collapse on the ground surface. After thawing, the soil becomes laminar in structure and roots grow horizontally in the surface soil instead of penetrating the subsoil."

__________ Tamura, S., and Yamanouchi, M. Investigation on freezing and thawing action in volcanic soil and remedial measures for soils and crops. 3. Jour. Sci. Soil and Manure [Tokyo] 25: 273-279. 1955. [In Japanese, with English summary.] (Abs. in Soils and Ferts. 18: 497. 1955.)

"Plowing after harvesting accelerated freezing."